New QCD-like strong interactions and the $t\bar{t}$ forward-backward asymmetry

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Plan

- Introduction
  - $t\bar{t}$ asymmetry measurements vs. SM predictions
  - weak scale flavor symmetric vectors
  - A_C vs. A_{FB}
- A QCD-like strong interaction realization

  J. Brod, J. Drobnak, A.K., E. Stamou, J. Zupan, to appear
  - the UV model
  - the weak scale resonances
  - phenomenology

Experiment vs SM

For $M_{t\bar{t}} > 450$ GeV CDF measures (lepton+jets):

$$A_{FB}^{t\bar{t}} = \frac{\sigma_F^{SM} + \sigma_F^{NP} - \sigma_B^{SM} - \sigma_B^{NP}}{\sigma_F^{SM} + \sigma_F^{NP} + \sigma_B^{SM} + \sigma_B^{NP}} = 0.295 \pm 0.066$$

SM NLO prediction for $M_{t\bar{t}} > 450$ GeV: Bernreuther, Si

$$A_{FB}^{t\bar{t}}\,(\mathrm{NLO}) = 0.129^{+0.008}_{-0.006} \qquad 2.4\sigma \text{ discrepancy}$$

SM prediction decreases by $\sim 30\%$ for $\sigma_{\mathrm{NLO}}^{t\bar{t}}$ in the denominator

For $M_{t\bar{t}} < 450$ GeV CDF measures:

$$A_{FB}^{t\bar{t}} = 0.084 \pm 0.053 \;\; \text{consistent with SM}$$

D0 does not see a significant $M_{t\bar{t}}$ dependence (not unfolded)

Inclusive $A_{FB}^{\bar{t}t}$ measurements (lepton + jets):

CDF:

$$A_{FB}^{\bar{t}t} = 0.196 \pm 0.065 \text{ (D0)}, \quad 0.164 \pm 0.045 \text{ (CDF)}$$

$$A_{FB}^{\bar{t}t}\,(\text{exp avg}) = 0.174 \pm 0.037 \text{ vs. } A_{FB}^{\bar{t}t}(\text{NLO SM}) = 0.088 \pm 0.006$$

The charge asymmetry A_C at the LHC

- the LHC is a symmetric collider (P-invariant) therefore $A_{FB}^{\bar{t}t} = 0$.

- can define a charge asymmetry using rapidity differences, which can access the physics responsible for $A_{FB}^{\bar{t}t}$ at the Tevatron:

$$A_C = \frac{N(\Delta|y| > 0) - N(\Delta|y| < 0)}{N(\Delta|y| > 0) - N(\Delta|y| < 0)}$$

$$\Delta|y| = |y_t| - |y_{\bar{t}}|$$

- dilution due to large $gg \to t\bar{t}$ means A_C is much smaller than $A_{FB}^{\bar{t}t}$.

- Experiment and SM theory are consistent

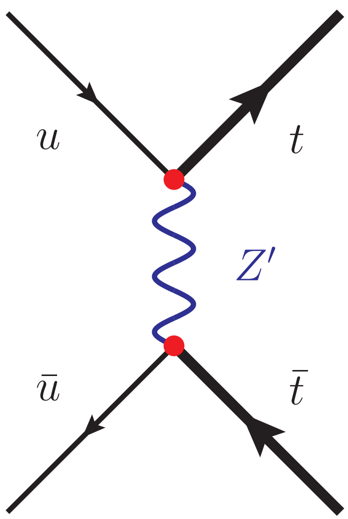
$$\sqrt{s} = 7 \text{ TeV}: \quad A_C^{\text{exp avg}} = 1.0 \pm 0.8\% \ \text{(CMS + ATLAS, semileptonic + dileptons)},$$
$$A_C = 1.23 \pm 0.05\% \ \text{(NLO SM)}$$

$$\sqrt{s} = 8 \text{ TeV}: \quad A_C = 0.5 \pm 0.9\% \ \text{(CMS, semileptonic)}, \quad 1.11 \pm 0.04\% \ \text{(NLO SM)}$$

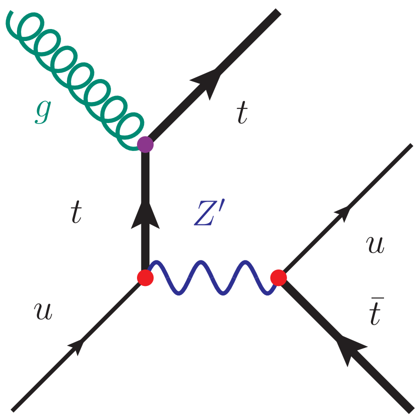
Low mass vector t-channel explanations

appealing features:

- Z' with mass of a few hundred GeV and $O(1)$ $Z' - u_R - t_R$ coupling yields large $A_{FB}^{t\bar{t}}$ Jung, Murayama, Pierce, Wells '10
  - t-channel top production more forward with increasing $M_{t\bar{t}}$
- simultaneously, good agreement with CDF measured spectrum at large $M_{t\bar{t}}$ Gresham, Kim, Zurek '11; Jung, Pierce, Wells '11
  - CDF's acceptance decreases rapidly at large rapidity



- correlation between NP enhancement of A_{FB} and A_c is broken
  J. Drobniak, A.K., J. Kamenik, G. Perez, J. Zupan;   Alvarez, Leskow



$$ug \to Z' t \to \bar{t}\, u + t, \qquad (\bar{u}g \to Z'\bar{t} \to t\bar{u} + \bar{t})$$

- for ug process Z' gets a boost due to larger momentum of u than g,

  $\Rightarrow$ boosted $\bar{t}$ relative to t, opposite to what happens in $u\bar{u} \to t\bar{t}$

  $\Rightarrow$ large negative contribution to A_C is possible issues:

- same sign top production $uu \rightarrow tt$, if Z' is self-conjugate
- $D - \bar{D}$ mixing: why is $(Z' - u - c) << (Z' - u - t)$
  - both problems solved if Z' is part of a vector flavor multiplet
    Grinstein, AK, Trott, Zupan

- contribution to $\sigma_{t\bar{t}}$ at LHC via single light mediator decay Gresham, Kim, Zurek

$$gq \to t + (Z' \to \bar{t}q)$$

- LHC bounds on top+jet resonance production
  - both problems solved if $\mathrm{Br}(Z' \to \bar{t}q)$ is suppressed, requires additional dominant Z' decay mode
  - $m_{Z'} \sim 200$ GeV and $\mathrm{Br}(Z' \to \bar{t}q) \sim 0.25$ compatible with large decrease in A_C, e.g. from $A_C = 0.03$ to 0.01
- additional $t + (Z' \to \bar{t}j)$ production maintains consistency with CMS measurements of jet multiplicity distribution in $t\bar{t}$ events Drobnak, AK, Kamenik, Perez, Zupan

Phenomenological flavor symmetric vector models

- Simplest viable possibilities are $U(3)_{U_R}$ or $U(2)_{U_R}$ flavor octet color singlet vectors coupling only to RH up quarks

$$\mathcal{L} = \lambda \, \bar{u}_R \, \gamma^\mu \, V_\mu \, u_R$$

- $V_\mu = V_\mu^A T^A$

$$\mathrm{t-channel} \quad \frac{1}{\sqrt{2}}(V_\mu^4 - iV_\mu^5)(\bar{t}_R \gamma^\mu u_R) + \mathrm{h.c.} \qquad \text{“}K^*\text{”}$$

$$\mathrm{s-channel} \quad \frac{1}{\sqrt{6}} V_\mu^8 \, (\bar{u}_R \gamma^\mu u_R + \bar{c}_R \gamma^\mu c_R - 2\bar{t}_R \gamma^\mu t_R) \qquad \text{“}\Phi/\omega\text{”}$$

$\Rightarrow$ $t\bar{t}$ production t-channel dominated

Strong interaction realization

Why strong interactions?

- two renormalizable options for UV completions
  - local horizontal symmetry flavor gauge bosons (FGB's)
  - composite vector meson flavor multiplets
- but sub-TEV FGB models problematic for FCNCs
- composite vector mesons naturally have new dominant channels for decay: $V \to PP$, e.g. $\rho \to \pi\pi$, $K^* \to K\pi$
  - required in low scale t-channel models: LHC $t\bar{t}$ xsec,...
  - favored by dijet constraints

The set-up

- a scaled up copy of QCD with three light flavors, with an additional heavy flavor scalar quark

- asymptotically free $SU(3)_{HC}$ “hypercolor" gauge interaction, chiral symmetry breaking scale $\Lambda_{HC} \sim 250$ GeV

- with $SU(2)_L$ singlet matter content:

  - color singlet flavor triplet hypercolor quarks $(\mathcal{Q}_{L_i}, \mathcal{Q}_{R_i}),\ i = u, c, t$

  - color triplet, flavor singlet hypercolor scalar $\mathcal{S}$

  - transformations under $SU(3)_{HC} \times SU(3)_C \times SU(2)_L \times U(1)_Y$

$$\mathcal{Q}_{L_i,R_i}(3,1,1,0), \quad \mathcal{S}(\bar{3},3,1,2/3)$$

Lagrangian:

$$\mathcal{L}_{NP} = \mathbf{h}_{ij}\, \bar{u}_{Ri}\, \mathcal{Q}_{Lj}\, \mathcal{S} + h.c. + \mathbf{m}_{\mathcal{Q}_{ij}}\, \bar{\mathcal{Q}}_i\, \mathcal{Q}_j + m_{\mathcal{S}}^2 |\mathcal{S}|^2$$

u_{Ri} are the usual RH up quarks (u_R, c_R, t_R),

- impose global $U(2)$ flavor symmetry: (u_R, c_R) and $(\mathcal{Q}_u, \mathcal{Q}_c)$ transform as doublets

$$\Rightarrow \ \mathbf{h} = \mathrm{diag}(h_1, h_1, h_3), \quad \mathbf{m}_{\mathcal{Q}} = \mathrm{diag}(m_{\mathcal{Q}_1}, m_{\mathcal{Q}_1}, m_{\mathcal{Q}_3})$$

- HC sector only couples to RH up quarks due to hypercharge assignments for $\mathcal{Q}$, $\mathcal{S}$
  $\Rightarrow$ do not single out RH up quarks directly for special treatment

- Spontaneous breaking of $U(2)$ or $U(2)^3$ flavor symmetry in the UV could generate the usual quark Yukawa hierarchies via Frogatt-Nielsen type mechanism

- At the weak scale would have SM $+$ flavor symmetric HC sector remnant

$$\mathcal{L}_{NP} = h_i \; \bar{u}_{Ri} \, \mathcal{Q}_{Li} \, \mathcal{S} + h.c. + m_{\mathcal{Q}_i} \; \bar{\mathcal{Q}}_i \, \mathcal{Q}_i + m_{\mathcal{S}}^2 |\mathcal{S}|^2$$

- UV parameters

$$h_i \sim 3, \;\; m_{\mathcal{Q}_1} \sim 3 \;\; \text{GeV}, \; m_{\mathcal{Q}_3} \sim 30 \;\; \text{GeV}, \;\; m_{\mathcal{S}} \sim 500 \; \text{GeV}$$

$$f_\pi \sim 20 \;\; \text{GeV} \;\; \Rightarrow \;\; \Lambda_{\text{HC}} \sim 4\pi f_\pi \sim 250 \; \text{GeV}$$

  - $m_{Q_i} << \Lambda_{HC}$ as in QCD
  - $m_{\mathcal{S}} = O(\text{few}) \times \Lambda_{HC} \Rightarrow$ heavy flavor with mass between “charm" and “bottom"

Hypercolor resonances

Phenomenology of interest is dominated by lowest lying resonances. Include following:

- flavor octet of color singlet pseudo-Nambu-Goldstone bosons: π^a_{HC}

$$\pi\,[\bar{\mathcal{Q}}_{1,2}\mathcal{Q}_{1,2}],\;\; K\,[\bar{\mathcal{Q}}_{1,2}\mathcal{Q}_3],\;\; \eta\,[\bar{\mathcal{Q}}_1\mathcal{Q}_1+\bar{\mathcal{Q}}_2\mathcal{Q}_2-2\bar{\mathcal{Q}}_3\mathcal{Q}_3]$$

- flavor nonets of color singlet “light-light" vectors and axial vectors: $\rho^a_{HC},\; a^a_{1\,HC}$

$$\rho\,[\bar{\mathcal{Q}}_{1,2}\mathcal{Q}_{1,2}],\;\; K^*\,[\bar{\mathcal{Q}}_{1,2}\mathcal{Q}_3],\;\; \phi\,[\bar{\mathcal{Q}}_3\mathcal{Q}_3],\;\; \omega\,[\bar{\mathcal{Q}}_1\mathcal{Q}_1+\bar{\mathcal{Q}}_2\mathcal{Q}_2]$$

- flavor triplet, weak singlet, “heavy-light" composite up quarks:

$$u'_{(L,R)}\,[\mathcal{Q}_1\,\mathcal{S}],\;\; c'_{(L,R)}\,[\mathcal{Q}_2\,\mathcal{S}],\;\; t'_{(L,R)}\,[\mathcal{Q}_3\,\mathcal{S}]$$

- flavor singlet P-wave vector “heavy-heavy" bound states of the HC scalars:

$$V_o\,[\mathcal{S}^*\mathcal{S}]\;(\text{color octet}),\qquad V_s\,[\mathcal{S}^*\mathcal{S}]\;(\text{color singlet})$$

- neglect η', $\eta-\eta'$ mixing; neglect 1^P_1 axial vectors, $K_{1A}-K_{1B}$ mixing

HC masses

- the HC condensate, decay constants, and resonance masses estimated via scaling from QCD

$$f_\pi = \frac{M_\chi}{m_\rho^{\mathrm{QCD}}} f_\pi^{\mathrm{QCD}}, \quad f_\rho = \frac{M_\chi}{m_\rho^{\mathrm{QCD}}} f_\rho^{\mathrm{QCD}}, \quad f_{a_1} = \frac{M_\chi}{m_\rho^{\mathrm{QCD}}} f_{a_1}^{\mathrm{QCD}}$$

where $M_\chi \equiv m_\rho$ in the chiral limit $m_\mathcal{Q} \to 0$

  - π^a masses via scaled up Gell-Mann, Oakes, Renner relation
  - ρ^a, a_1^a masses via simplified quark model for QCD, scaled up to M_χ

$$M_\chi, m_{\mathcal{Q}_1}, m_{\mathcal{Q}_3} \Rightarrow m_{\rho^a}, m_{a_1^a}$$

$+ \ \phi - \omega$ and $f_1^0 - f_1^8$ mixing angles

  - u', c', t' and $V_{o,s}$ masses via approximate heavy-light and heavy-heavy meson mass formulas:

$$M_{u'_i} = M_\chi + m_{\mathcal{Q}_i} + m_\mathcal{S}$$

$$M_{V_{o,s}} = (m_{a_1}/m_\rho)_{\mathrm{QCD}} M_\chi + 2m_\mathcal{S}$$

HC interactions

- couplings among HC resonances estimated via vector meson dominance (VMD), naive dimensional analysis (NDA), and scaling from QCD

$$g_{\rho\pi\pi}\, f_{abc}\, \rho^a_\mu \pi^b \partial^\mu \pi^c + g_\rho\, \rho^a_\mu\; \bar{u}'\, T^a\, \gamma^\mu\, u' + g_{a_1}\; a^a_{1\,\mu}\; \bar{u}'\, T^a\, \gamma^\mu\, \gamma_5\, u' + g_{V_o} \bar{u}'_i \mathcal{T}^a \gamma_\mu u'_i V_o^{a\,\mu}$$

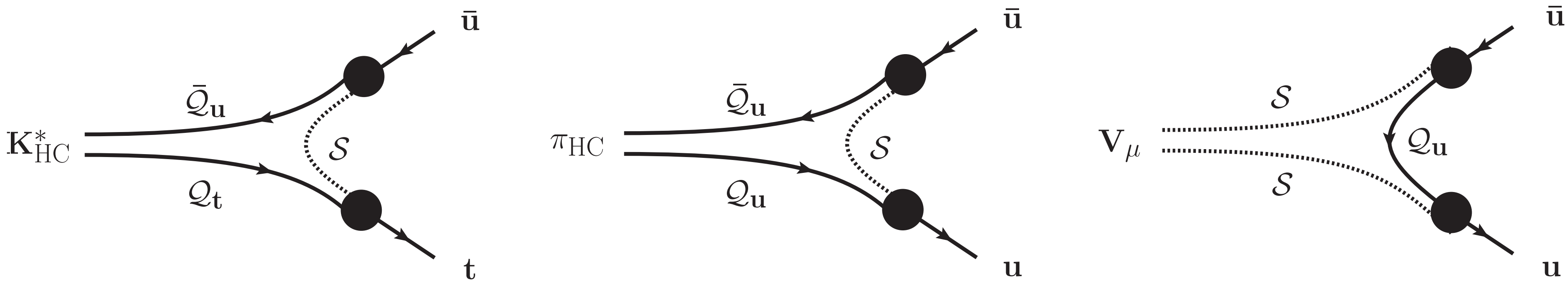
$$+ g_{V_s} \bar{u}'_i \gamma_\mu u'_i V_s^\mu \;+\; \frac{g_A}{f_\pi}\, \left(\bar{u}'_R\, T^a\, \not{\partial}\pi^a\, u'_R - \bar{u}'_L\, T^a\, \not{\partial}\pi^a\, u'_L\right) + \cdots$$

$$\text{VMD} \;\Rightarrow\; g_{\rho\pi\pi} \approx g_\rho \approx \frac{m_\rho}{f_\rho}, \quad g_{a_1} \approx \frac{m_{a_1}}{f_{a_1}}, \quad g_{V_o} \approx \frac{M_{V_o}}{f_{V_o}}$$

- Take $g_A \approx 1$, consistent with NDA, as well as normalized $B^* B\pi$, $D^* D\pi$ couplings ($\hat{g} \simeq 0.6 - 0.7$), and nucleon-pion coupling ($g_A^{\rm QCD} \simeq 1.26$)
- to estimate $f_{V_{o,s}}$, interpolate between $f_{J/\psi}$ and f_Υ in QCD, scale to HC

HC couplings to quarks

- partial compositeness: ordinary and composite up quarks mix via the Yukawa couplings $h_i \bar{u}_{iR} \mathcal{Q}_{iL} \mathcal{S}$
  - mass mixing terms: $\sqrt{2}\, h_i\, f_{u'}\, \bar{u}_{Ri}\, u'{}_{Li}$,
    where $f_{u'}$ is the composite quark decay constant: $\langle u'_i | \bar{\mathcal{Q}}_i\, \mathcal{S}^* | 0 \rangle = \sqrt{2}\, f'_u\, \bar{u}'_i$
  - to estimate $f_{u'}$, interpolate between light-light (ρ, K^*) and heavy-light (D^*, B^*) decay constants in QCD, scale to HC
  - composite admixture: $\approx 20-40\%$ (u_{Ri}) ; $\approx 10\%$ (t_L), $\approx 0\%$ $(u_L\, , c_L)$



HC decays

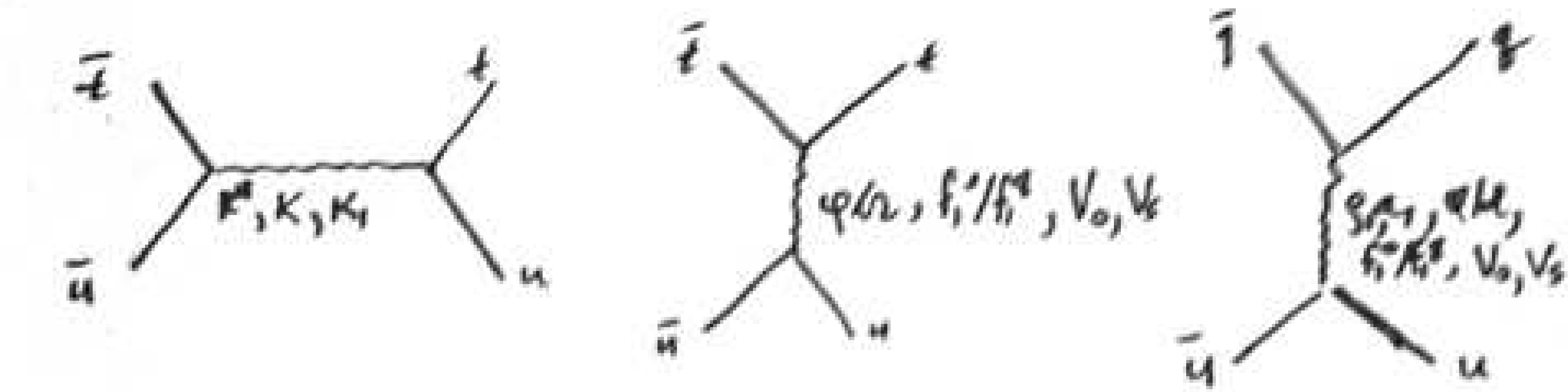
- $\rho \to \pi\pi \;\Rightarrow\; \Gamma/M = O(10\%)$, good for dijets
- $K^* \to K\pi \;\Rightarrow\; \mathrm{Br}(K^* \to \bar{u}t) \simeq 20 - 30\%$ can be obtained
- pions and kaons have narrow widths: $\pi \to 2j, \quad K \to jt^*$
- composite quark decays dominated by $u'_i \to u_j + n\,\pi^a$
  - total widths approximated by width of partonic decay $\mathcal{S} \to u_i \bar{\mathcal{Q}}_i$ similar to partonic approximation for inclusive B and D meson widths
  - Yukawa couplings $h_i \sim 3 \;\Rightarrow\;$ composite quarks are broad, $\Gamma/M = O(20\%)$
- $V_{o,s}$ decay widths are large, dominated by

$$V_{o,s} \to u'\bar{u} + n\,\pi, \quad n = 0, 1, \ldots.$$

  - summing over two body decay widths $\Rightarrow\; \Gamma/M \sim O(30\%)$, good for $M_{t\bar{t}}$ spectrum, dijets

HC mediated $t\bar{t}$ and dijet production

- t-channel $t\bar{t}$ amplitudes via K^*, K_1, K exchange
- s-channel $t\bar{t}$ amplitudes via exchange of
  - ϕ, ω: highly suppressed by $\phi - \omega$ mixing
  - f_1^0, f_1^8: highly suppressed by $f_1^0 - f_1^8$ mixing
  - V_o, V_s
- s-channel and t-channel dijet production via ρ, a_1, ϕ/ω, f_1^0/f_1^8, $V_{o,s}$ exchange



A light t-channel benchmark

- UV inputs for benchmark:

$$M^{HC} = 171 \text{ GeV}, \;\; m_{\mathcal{Q}_1} = 3.1 \text{ GeV}, \;\; m_{\mathcal{Q}_3} = 30.5 \text{ GeV},$$

$$m_{\mathcal{S}} = 520 \text{ GeV}, \;\; h_1 = 2, \;\; h_3 = 4.2$$

$\mu = 2m_t$ ren. scale for LO new physics contributions to asymmetries, cross sections

- resonance mass outputs:

$$M_\pi = 62 \text{ GeV}, \;\; M_K = 143 \text{ GeV}, ...; M_\rho = 177 \text{ GeV}, \;\; M_{K*} = 211 \text{ GeV}, ...$$

$$M_{a_1} = 273 \text{ GeV}, \;\; M_{K_1} = 295 \;\text{ GeV}, ...$$

$$M_{u'} = M_{c'} = 691 \text{ GeV}, \;\; M_{t'} = 718 \;\text{ GeV}; \quad M_{V_{o,s}} = 1292 \text{ GeV}$$

- asymmetries (experiment in parenthesis):

$$A_{\rm FB}^{\rm inc} = 0.191\,(.175{\pm}0.038), \quad A_{\rm FB}^{\rm low} = 0.096\,(0.084{\pm}0.055), \quad A_{\rm FB}^{\rm high} = 0.327\,(0.295{\pm}0.067)$$

$$A_C^{\rm inc,7TeV} = 0.018\ (0.010 \pm 0.008), \quad A_C^{\rm inc,8TeV} = 0.017\ (0.005 \pm 0.009)$$

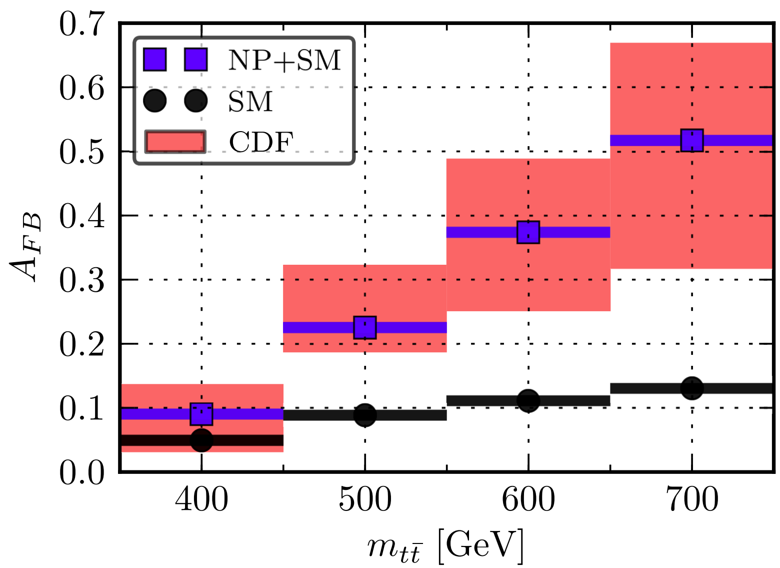
- total $t\bar{t}$ cross sections (experiment in parenthesis)

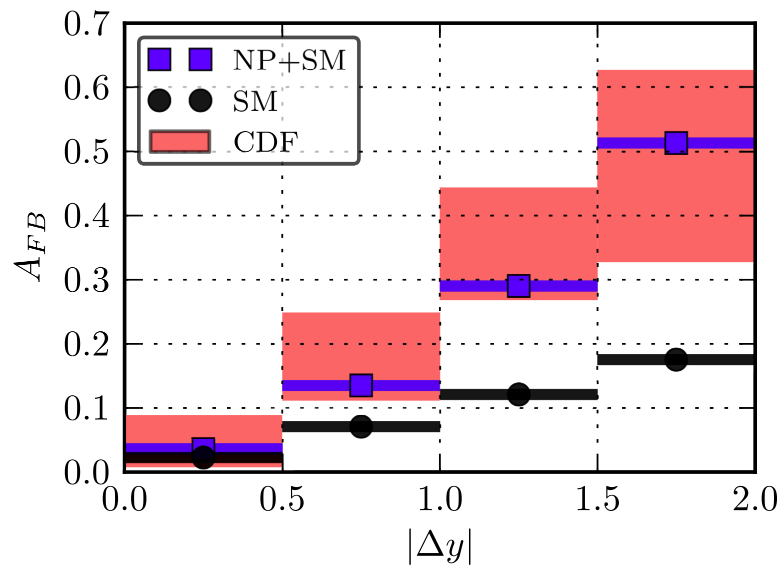
$$\sigma^{\rm TEV,inc} = 6.53 \pm 0.54\ (7.60 \pm 0.41)\,{\rm pb}, \quad \sigma^{\rm LHC,inc} = 177 \pm 15\ (172.5 \pm 15)\,{\rm pb}$$

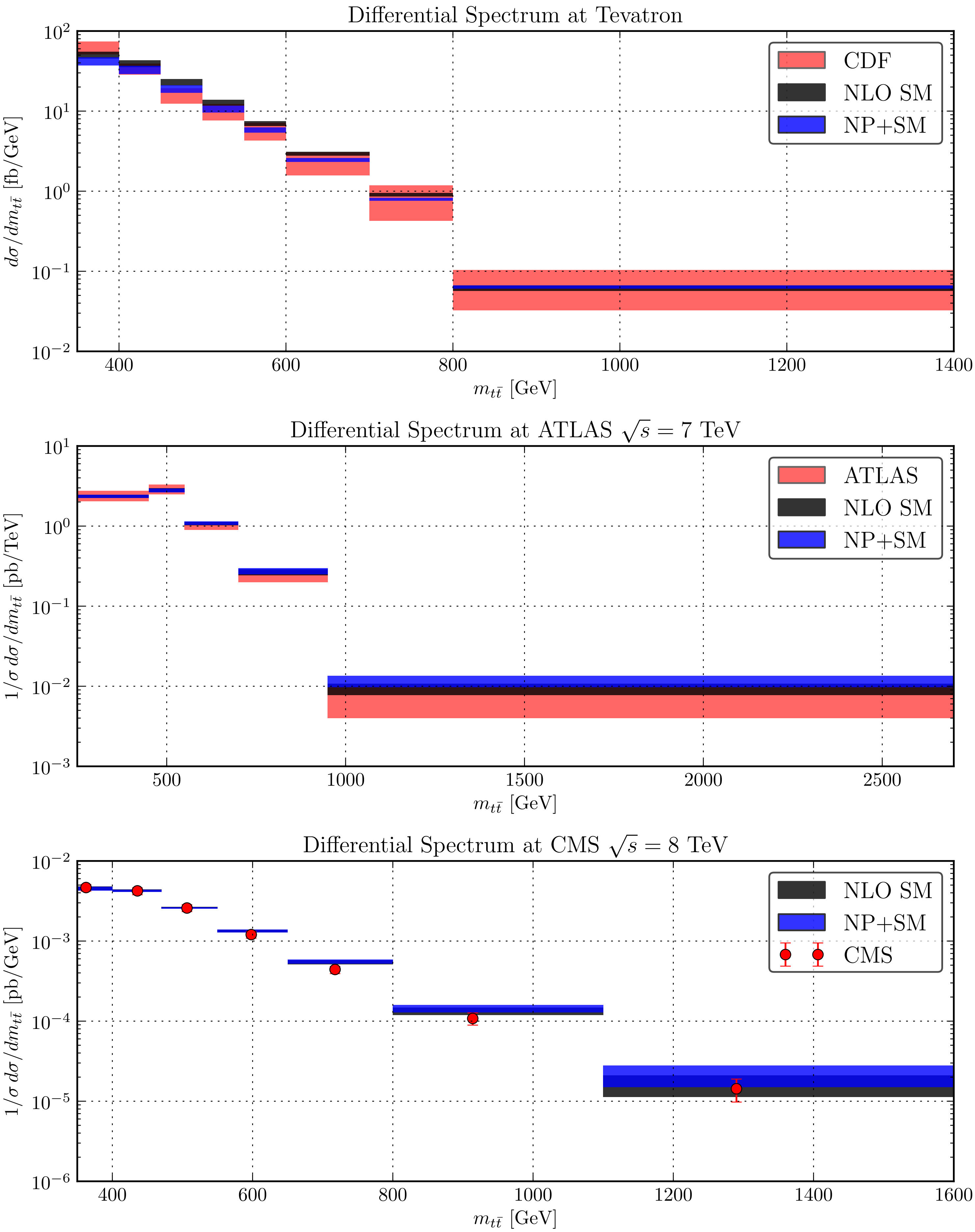
benchmark cross section uncertainties are the SM contribution NNLO errors

Differential asymmetries at Tevatron

- obtained partonically in MG

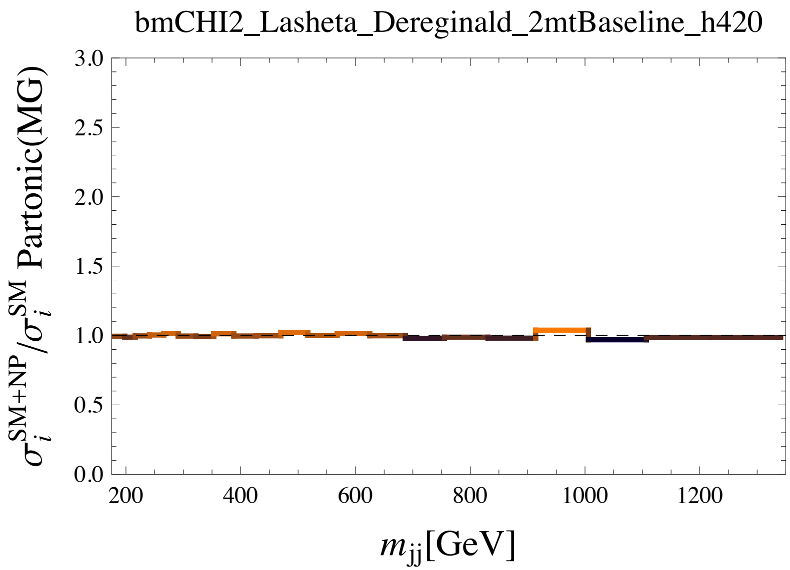


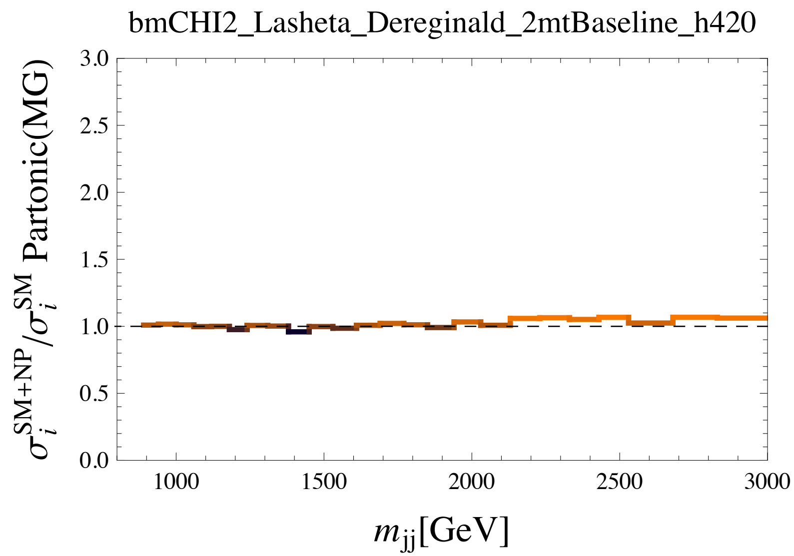




Differential Spectrum at Tevatron
$d\sigma/dm_{t\bar{t}}$ [fb/GeV]
$m_{t\bar{t}}$ [GeV]
CDF
NLO SM
NP+SM
Differential Spectrum at ATLAS $\sqrt{s} = 7$ TeV
$1/\sigma\, d\sigma/dm_{t\bar{t}}$ [pb/TeV]
$m_{t\bar{t}}$ [GeV]
ATLAS
NLO SM
NP+SM
Differential Spectrum at CMS $\sqrt{s} = 8$ TeV
$1/\sigma\, d\sigma/dm_{t\bar{t}}$ [pb/GeV]
$m_{t\bar{t}}$ [GeV]
NLO SM
NP+SM
CMS

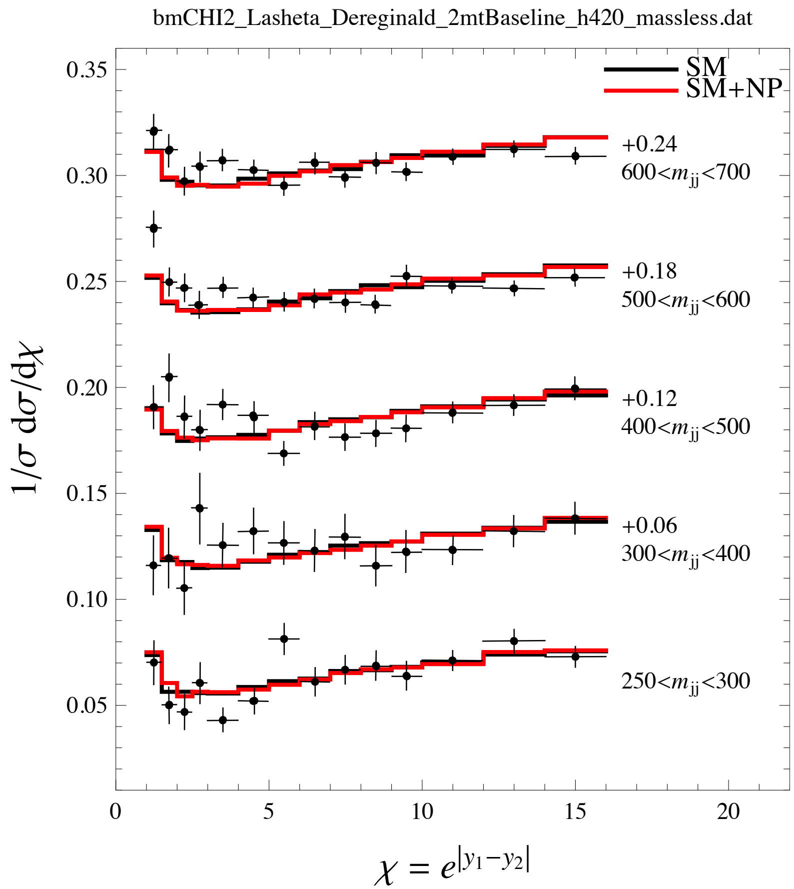
dijet m_{jj} spectra

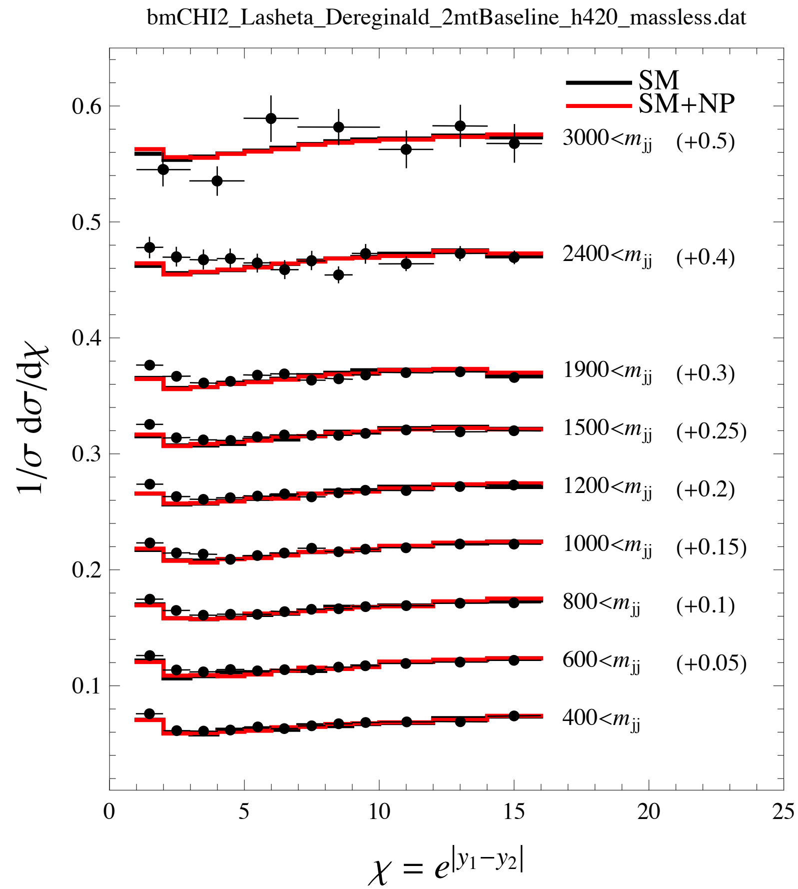




- ratios of benchmark to SM predictions for Tevatron (left), LHC (right), obtained partonically in MG

dijet angular correlations





- ratios of benchmark to SM predictions for Tevatron (left), LHC (right), obtained partonically in MG; data from D0 and CMS

dijet pair production

- CDF has bounds on $p\bar{p} \to X \to YY \to (jj)(jj)$ in $m_X - m_Y$ plane 1303.2699

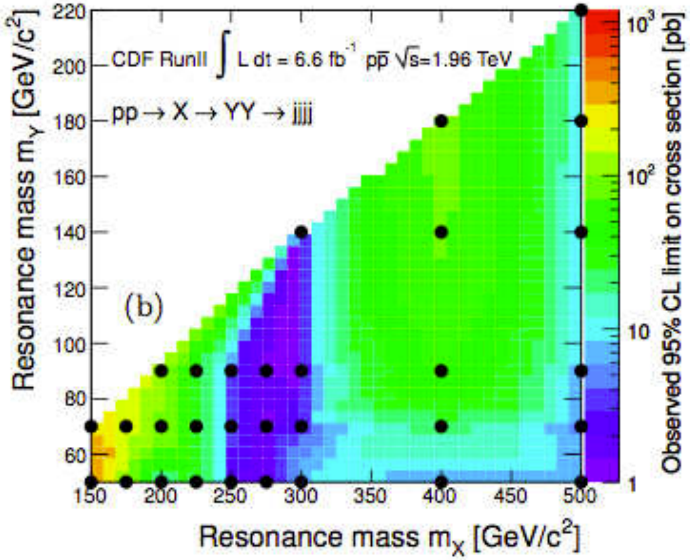


TABLE II: Observed and expected 95% C.L. upper limits on $\sigma(p\bar{p} \to X \to YY \to jj\ jj)$ for several values of m_Y and m_X. Also shown are theoretical predictions for axi-gluon production assuming coupling to quarks of $C_q = 0.4$ [5, 9].

m_X (GeV/c^2)	m_Y (GeV/c^2)	Expected (pb)	Observed (pb)	Axi-gluon (pb)
150	50	641.2	431.1	5600
	70	209.6	270.6	
175	50	66.8	78.9	3500
	70	111.5	163.9	
200	50	13.8	9.5	2200
	70	30.4	91.5	
	90	17.8	100.4	
225	50	18.0	26.0	1750
	70	20.7	25.0	
	90	20.9	25.3	
250	50	6.2	2.0	1000
	70	4.0	3.6	
	90	5.1	2.8	

- constrains $p\bar{p} \to \rho \to \pi\pi \to (jj)(jj)$
  - for $m_\rho \approx 177$ GeV, $m_\pi \approx 63$, $\sigma(p\bar{p} \to \rho \to \pi\pi \to (jj)(jj)) \approx 80\,(100)$ pb at LO (with NLO K-factor), apparently consistent with CDF bound

Associated K^* production at LHC, Tevatron

- at 7 TeV: $\sigma(pp \to K^* t) = 13.6$ pb; $\mathrm{Br}(K^* \to u\bar{t}) = 32\%$
  - reduction in A_C from 0.029 to 0.018 via $K^* \to \bar{u}t$
  - ATLAS (7 TeV) top + jet resonance searches:

$$\sigma(pp \to K^* t) \times \mathrm{Br}(K^* \to u\bar{t}) \approx 20\% \times \text{ATLAS bound}$$

  - CDF top + jet resonance searches:

$$\sigma(p\bar{p} \to K^* t) \times \mathrm{Br}(K^* \to u\bar{t}) \approx 12\% \times \text{CDF bound}$$

Associated K production at LHC

- $\sigma(pp \to Kt \to \bar{t}^* \, u \, t) = 18$ pb (7 TeV), 24 pb (8 TeV)
  - what about spill over into single-top Wt (dilepton) signal region, or $t\bar{t}$ signal regions?

    LO MG analysis $\Rightarrow$ softer Kt lepton p_T significantly reduces leakage into the signal regions:

    - Kt dilepton xsec contribution < 1.7 pb to CMS measurement
      $\sigma(pp \to Wt) = 16^{+5}_{-4}$ pb (7 TeV) [1209.3489]
    - Kt dilepton xsec contribution < 11 pb to CMS (dilepton) measurement
      $\sigma(pp \to t\bar{t}) = 239 \pm 13$ (8 TeV) [1312.7582]

Composite u_i' production

- $\sigma(pp \to t'\bar{t}', u'\bar{u}') \approx 1$ pb (8 TeV), 7 pb (13 TeV) with $m_{u_i'} \approx 700$ GeV

- detection at LHC is challenging: decay modes $u_i' \to u_j + \pi^a\,'s$, u_i' widths $\Gamma/M \sim 20\%$, and

$$\mathrm{Br}(t' \to t + X) \sim \mathrm{Br}(u' \to t\bar{t}^* + X) \sim 1/3$$

  - π^a are color singlets, decay via $\pi \to j\,j$, or $K \to \bar{t}^* j$
  - $\Rightarrow$ final states with two tops have many additional jets, e.g., $\bar{t}'t' \to \bar{t}\,t$ + n jets

- single u_i' production more promising: $\sigma(t'\bar{t}) \sim 3-8$ pb (8 TeV), 10 -30 pb (13 TeV)

- “same sign" $u'u'$ pair production: $\sigma(u'u') \sim 3-20$ pb (8 TeV), 9 - 60 pb (13 TeV)

  - $\mathrm{Br} \sim 10\%$ to $t\,t\,\bar{t}^*\bar{t}^*$ + n jets final states, could show up as same sign top pairs + many jets

Conclusion

- strong interaction realization of flavor symmetric t-channel origin for A_{FB}
- copy of QCD with 3 light flavor quarks, and a heavy flavor scalar
- in the IR leads to an even bigger zoo of resonances than QCD, e.g. additional composite quarks, additional decay modes....
- excellent illustration of the challenges faced by LHC in BSM searches:
  - the lowest lying resonances are color singlets
  - the heavier colored resonances are broad, decay to multi jet final states
- negligible contributions to precision electroweak parameters S, T
- new contributions to atomic parity violation easily consistent with current bounds
- the lightest HC baryon, e.g., $[\mathcal{Q}_u\mathcal{Q}_u\mathcal{Q}_c]$, may provide an example of flavorful DM